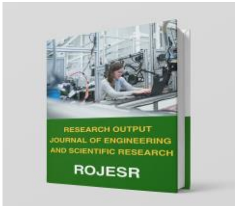

Research Output Journal of Engineering and Scientific Research 3(1):17-22, 2024

ROJESR Publications ISSN: 1115-6155

https://rojournals.org/roj-engineering-and-scientific-research/

Advancements in Carbon Capture and Utilization (CCU) Technologies

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ABSTRACT

Carbon capture and utilization (CCU) technologies are critical in mitigating climate change by capturing CO2 emissions and converting them into valuable products. This comprehensive overview explores recent advancements in CCU technologies, including various capture methods such as pre-combustion, post-combustion, and oxyfuel combustion. It delves into the utilization of captured carbon in enhanced oil recovery, building materials, and the production of fuels and chemicals. The book highlights technological innovations, economic considerations, and future research directions, emphasizing the potential of CCU to reduce greenhouse gas emissions and create economic value.

Keywords: Carbon Capture, Carbon Utilization, Climate Change Mitigation, Pre-combustion Capture, Post-combustion Capture.

INTRODUCTION

A wide range of carbon capture and utilization (CCU) approaches, whereby CO2 is captured and utilized in industrial processes, are being developed to mitigate climate change. This 11-chapter book provides a comprehensive overview of the technological advancements and benefits of CCU technologies, updates about various CCU developments, and information on various funding and incentives available for CCU approaches [1].

TYPES OF CARBON CAPTURE TECHNOLOGIES

There have been a number of developments in the separation and purification technologies of CO2. These can be broadly classified into: physical adsorption, chemical adsorption, membrane separation, cryogenic separation, pressure swing adsorption, and absorption. The conventional and post-combustion methods have higher energy disadvantages. However, the pre-combustion methods have lower energy disadvantages. The solid sorbent working on chemical reaction use fuels in their regeneration and provide more CO2 for the transport, utilization, and storage. The (mainly aqueous) amine-based solvents and their mixtures are currently the most preferred in the post-combustion CO2 capture because of their high capacities for CO2 absorption. However, these are very energy-intensive and are economically unattractive [2]. In the pre-combustion capture, since the gases are free of impurities like nitrogen and are rich in CO2, the SELEXOL process, used for natural gas and hydrogen production, can easily be retrofitted for CO2 capture. The most commonly used membranes for capturing CO2 are H2-containing glassy polymers, H2-facilitated mixed method for capturing the CO2 during the pre-combustion cleaning from hydrogen-containing fuel, and H2-facilitated asymmetric gases non-glassy membranes for separating flue gases, which are hydrogen-free. For options like CO2 enhanced oil recovery, combining the chemical treatment methods with the MEA or mixed surfactant systems are used. The chemicals in the chemical adsorption method are continually recycled, which renders it to be an energy-friendly method. The type of feasible carbon capture will depend on physical, chemical, environmental, and economic considerations [3].

PRE-COMBUSTION CAPTURE

In pre-combustion capture, the carbon-containing fuel is transformed to form a combination of hydrogen and CO_2 before combustion. This can take the form of a natural gas reformer with the gas shifted and an acid gas separation unit to separate the CO_2 for subsequent storage. The synthesis gas from the reformer can be used directly in gas turbines to replace natural gas. This technology can also be applied to other CO_2-sequestering energy systems like coal gasification and non-biological production of biofuels based on Fischer-Tropsch synthesis. Due to the high concentrations of CO_2 in the pre-combustion gas stream, the CO_2 concentration can be increased to a level to ensure high efficiency and low power penalty using advanced chemical or physical solvent-based CO_2 capture technology. Power plants using hydrogen or a pre-combustion reformer have a higher specific power output but with higher capital costs than the other post-combustion based systems. The specific realizes costs of pre-combustion capture at present are similar to other chemical solvent-based capture technologies [4]. Another advanced solvent-based technology of interest is the use of advanced solvents with aqueous blends of amines that are heat stable at higher stripping temperatures, or that have reduced vapor pressure at lower energies absorption and reduced corrosion characteristics than the existing solvents such as MEA, DEA, and MDEA. The use of aqueous blends of amines allows supplementary amines that facilitate CO_2 desorption at lower temperatures and reduce the circulating load which can help reduce corrosive degradation. The choice of advanced solvent would depend on the specific characteristics of the flue gas and cost of solvents and support infrastructure. Carbone scientific AD-1200 and other sterically hindered amines with less hazardous or toxic properties without sacrificing performance have been developed. The use of impregnated resin particles and structured adsorbent beds offering the potential for recovery of CO_2 in an adsorber/regenerator system has been proposed [5].

POST-COMBUSTION CAPTURE

This is the commonly employed method where the CO_2 is captured from the flue gas after combustion. Implementation of post-combustion capture technologies will lead to a general decrease in the efficiency of the power plant due to the extra energy required to separate CO_2 from the flue gas so as not to contaminate the environment with the poisonous gas. End-of-pipe technique utilizes a solvent such as amines to capture CO_2 from the flue gas before it is stripped, i.e., CO_2 removal where absorption of CO_2 occurs, as shown in Eq. (2) (CO_2 absorption) and Eq. (3) (stripping of CO_2 from the solvent) [6]. Given that flue gas from combustion of coal and biomass has a low CO_2 concentration about 13% and 4%, respectively, the established absorption process follows a two-stage absorption process which is highly energy demanding. Using solid absorbents may possibly lessen the two-stage absorption to a single stage process with a lower energy consumption for natural gas-fired combustion power plant. However, the quandary lies in solvent handling and management, and the incurred high initial cost notwithstanding the non-appropriateness of the properties of the solvents. The presence of hazardous substances and lack of substantial chemical stability compounds the limitations of the above techniques. Alternatively, integration of membrane (polymeric) and/or other separation processes in the capture call for lesser energy, i.e., DEPOL (Dual end membrane: wide temperature dehumidification and LNG regeneration Process) process and/or MEHU MSV-pMDA process. The MEJO (membrane extractor with jet to the origin) and HYBRIM (hydrophobic asymmetric membrane with enhanced flux and resistance) are to incidence the limitations of solvent abuse. In summary, the integration of other techniques to improve post-combustion capture and to reduce global CO_2 emissions can be stand-alone or combined, serving as a further context for the CCU innovations or the breakthroughs [7].

OXYFUEL COMBUSTION CAPTURE

Oxyfuel combustion is a technology where instead of air, oxygen is used as the oxidant in the combustion process. When this is done in a power plant with a steam turbine, the fuel reacts with pure oxygen in the boiler at high temperatures to produce flue gas mainly composed of CO_2 and water in vapor form from the elastic reaction. This vapor in the flue gas facilitates the separation of CO_2 from the other components and hence the cost of capturing CO_2 in the power plant is expected to reduce by 25-30% using oxyfuel combustion over conventional air combustion. Crest test case in oxyfuel combustion conditions under Hercules constraints the potentially varied and multi-scale potential troubleshooting platform in order of compare state-level goals, the carbon-optimize the remaining energy system [8]. The initial investment cost is due to the high capital cost of a separation unit, increased costs in compressing of the CO_2-rich stream(s) and other important factors for this technology option. The efficiency of the plant can also be lower than air combustion, impacting overall operational costs. The effect of different bases for the oxygen and fuel requirements on the energy efficiency was assessed through process integration. The result indicates that the actual implementation approach has a significant impact on the overall performance and the exhaust gas heat energy recovery potential. Oxyfuel combustion is a technology option where the benefits largely depend on many options. The gains can be substantial for certain situations as was demonstrated for the present study [9].

UTILIZATION OF CAPTURED CARBON

Currently, the utilization of captured carbon can be sorted into three main types. One type is the conversion of the captured CO_2 into useful fuels or chemicals (chemical conversion). This type of utilization comprises artificial photosynthesis and the classic catalytic reduction utilizing renewable energy, chemical, solar, and photo-catalytic, electrocatalytic, and biological conversion [10]. The second type of utilization comprises the production of building energy materials or industrial process materials (material conversion). This type of captured carbon utilization converts CO_2 to stable mineral carbonates or hydroxides by using natural rock or construction waste. The materials-centered method hydrothermal or mineralization is suitable for this purpose [11]. The third type is a grand new domain that belongs to the biomass-centered field. The captured CO_2 serves as advanced carbon nutrition for microalgae cultivation, which in turn serves as feedstock for food, fuel, chemicals, or advanced materials. Algae cultivation also includes nutrient, fertilizer, and waste treatment [12].

In the stage development of CCU technology and application, especially CO_2 storage against global warming, is in a critical phase. This chapter introduces several important concepts, divides them into several types, and introduces the principles, key research directions, recent development status, and future directions. The CCU utilization technology introduced in this book will help in timely attention to its values and implement better CO_2 reduction [13].

ENHANCED OIL RECOVERY

Obviously, this technology entrance as part of the energy industry may have a tendency toward oil, so the carbon-related sequestration they might achieve will mean more oil or other fossil fuel hauled from the ground somewhere else, producing emissions. In studies, the alcohol fuel could still be 80 percent lower in net carbon content than conventional gasoline or diesel. Carbon-conscious Americans may disapprove of purchasing a gasoline product, even though the emissions produced for each mile of driving are substantially lower. Some non-alcohol products from captured carbon show potential for very significant net carbon reductions. Consumers experience syllogistic bumps and humps, which may pose substantial obstacles to product marketing [14]. This realization about consumer-product expectations versus carbon content may initially be unsettling and unappetizing, especially if it appears to upset a sincere belief that the switch from conventional gasoline to an ethanol-gasoline mixture can engender a substantial average life cycle reduction in greenhouse gas emissions. Yet, after reviewing the available life cycle studies of gasoline, ethanol, and the two mixed together, the first author has doubted the conventional wisdom for several years. Transpiration of ethanol-fueled life cycle betterments into vehicle fuel markets may be difficult. Subsidies may be needed to encourage the development of integrated biorefineries that duplicate and advance the acceptable social value of these benefits. They won't come automatically, particularly if carbon emissions associated with utilization itself become suspect [15].

CARBON UTILIZATION IN BUILDING MATERIALS

Concrete production, which is the single most used and most abundant building material on Earth, depends on cement particles to hold it together. Since about 5-8% of the world's CO_2 emissions come from cement kilns fired in the process of manufacturing the powdered cement that goes into concrete, carbon can be effectively reduced by replacing some or all of it (cement) with waste materials that have a high lime content or by using the CO_2 waste from power plants to produce a cement-like binder without releasing the CO_2 into the atmosphere. Thus, waste forms of other materials which contain a large amount of lime, such as steel and aluminum refining slag, can be mixed with coal and iron for use in road paving, cement, or drainage applications instead of just allowing them to accumulate in huge quantities. Wildlife conservation and pollution-free coal, iron and concrete-producing power plants that sequester CO_2 waste in building materials and roads as fillers are the environmental pay-offs of the new treatments of CO_2 from the flue gases. More dignified burial for the other intended fillers, or long-term storage for reduction of CO_2 waste at the cost of $25/tonne, are costly options [16]. Magnesium silicate concrete is another binder that has been claimed to attract global interest as well as the anthropogenic CO_2 produced to help manufacture it. Croatians, evaluating Marxist Bitko's 1971 U.S. patent No. 3,657,130, for manufacturing basic magnesium carbonate and magnesium oxide reacted from sea salt by CO_2 injected from waste-fired plants, because of the heat generated by mixing it with alkaline earth metal silicate (mined as a waste product from the titanium and aluminum refining industries), studied the apartments of magnesium silicate concrete without releasing the CO_2 back into the atmosphere as part of the matrix.

The correct temperature and pressure are required to make magnesite at a cost of one-tenth from magnesium hydroxide, which was fired under an atmosphere of industrial waste [3].

CARBON UTILIZATION IN FUELS AND CHEMICALS

Advanced CCU technologies can target CO_2 as a C1 carbon atom feedstock to produce chemicals with higher carbon content than CH_4 and cheaper than biomass or waste. Several technologies have been developed for the conversion of CO_2 and associated hydrogen into carbon-based fuels, such as methane, methanol or dimethyl ether, and other higher-value commodities, with the various targets having differing carbon content. These technologies can be classified under the categories described below, considering chemical effects on catalysts [17].

(a) Methanation: Hydrogenation of CO_2 with H_2 or syngas to produce (renewable) methane, or synthetic natural gas for commodity energy use has been widely covered in recent review articles. The technology competes with the direct production of renewable methane from electrolytic hydrogen and CO_2 from air, although it might have some edges for local use if underground natural gas infrastructure is at hand, especially if associated non-separable CO_2 is valorized efficiently [18].

(b) Carbonylation: Insertion of a CO_2 molecule in the C-H bond of a hydrocarbon with a transition metal catalyst, leading to carbonic acids, carbonates, formamides, among other oxygenates. This technology converts CO_2 to carbon-carbon or carbon-organic bonds, targeting high-carbon emission products in the air and high-price commodity chemicals. However, the catalyst material selectivity of the products has yet to properly address this niche [19].

(c) Hydrocarboxylation: Another way to convert CO_2 to high-carbon emission products, typically C6 aromatic di- and tri-carboxylic acids, from arenes and alkenes in mild conditions or electrolyte fermentation cells. Similar to carbonylation, new bimetallic catalysts/adsorbents/membranes are being developed to improve the transformational outcomes associated with low processing costs [20].

CHALLENGES AND OPPORTUNITIES IN CCU TECHNOLOGIES

Carbon capture and utilization (CCU) technologies refer to the capture of carbon dioxide (CO_2) from emission sources and the direct utilization of the captured CO_2 as feedstock or for producing value-added chemicals and high-value advanced products. The earliest utilization of CO_2 captured from emission streams primarily focused on enhanced oil recovery (EOR) and enhanced gas recovery (EGR) from mature petroleum reservoirs. More recent and more sustainable CCU projects have focused on the direct chemical fixation of the captured CO_2 as part of the chemical manufacturing value chain. In addition to chemicals and polymers, CO_2 can also be utilized as carbon sources for biomatter synthesis, methanation of low concentrations of CO_2 and H_2 to produce synthetic natural gas (SNG) from renewable electricity, and electrochemical reduction of CO_2 [21]. The idea of integrating CO_2 utilization with carbon capture was proposed around the turn of the 21st century. Despite the intention to co-capture and utilize CO_2 in a single process train, the study of direct CCU of the captured CO_2 is less comprehensive than that of CO_2 capture. Direct CO_2 utilization is faced with multiple technological and economic challenges [22].

FUTURE TRENDS AND RESEARCH DIRECTIONS

Carbon dioxide utilization and consumer products are a direct, efficient, and inexpensive method for reducing CO_2 emissions. The Spanish Ministry of the Environment defines these technologies as carbon capture and utilization technologies, and the European Technology Platform Suschem considers them as innovative technologies that aim to mitigate climate change while creating economic and social value. Technologies for the capture of CO_2 have evolved, enabling the commercial use of CO_2 in various products and utilities. In this regard, the industry has identified carbon capture and use (CCU) as a key aspect of the European industrial strategy and different energy efficiency strategies. Funding programs at the regional, national, European, and international levels support these initiatives [23]. Currently, there are numerous examples of consumer products made with CO_2, agricultural projects utilizing CO_2, and recent applications of CO_2 for human health, such as the inhalation of CO_2-N_2O mixtures to restore a lost semiconsciousness state after loss of consciousness. Various organizations, including the IEA, the United Nations, and the European Union, recognize the potential of these technologies and are urging industry and governments to advance and maintain investment in research and development. The objective of this work is to conduct a technical evaluation of the existing information on CO_2 capture in the industry, as well as to propose future research directions that encompass all technologies and aspects, including those beyond climate change mitigation [24].

CONCLUSION

The advancements in carbon capture and utilization (CCU) technologies offer promising solutions to mitigate climate change by reducing CO_2 emissions and transforming them into valuable products. The diverse methods of capturing CO_2, including pre-combustion, post-combustion, and oxyfuel combustion, each present unique benefits and challenges. Utilization of captured carbon in enhanced oil recovery, construction materials, and chemical production demonstrates the versatility and economic potential of CCU technologies. Continued research and innovation are crucial to overcoming current limitations and enhancing the efficiency and cost-effectiveness of these technologies. The future of CCU lies in integrated approaches that maximize environmental and economic benefits, contributing significantly to global efforts in reducing greenhouse gas emissions and combating climate change.

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CITATION: Jean-Pierre Innocent Niyonkuru. Advancements in Carbon Capture and Utilization (CCU) Technologies. Research Output Journal of Engineering and Scientific Research. 2024 3(1):17-22.